A Search for Charged Massive Long-Lived Particles at D0

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Parallel Session 3 : F Collider exp and pheno

Motivation

- **Many beyond Standard Model(SM) theories predict Massive Long-Lived Particles(MLLPs)**

- **Existence of these particles can give us the answer that the present models can not solve yet**
  - **Lithium abundance in the present Big Bang Nucleosynthesis**
  - **MLLP that decays during or after BBN can be a possible solution**

- **We're looking for Charged Massive Long-lived Particles(CMLLPs) at the D0 experiment**

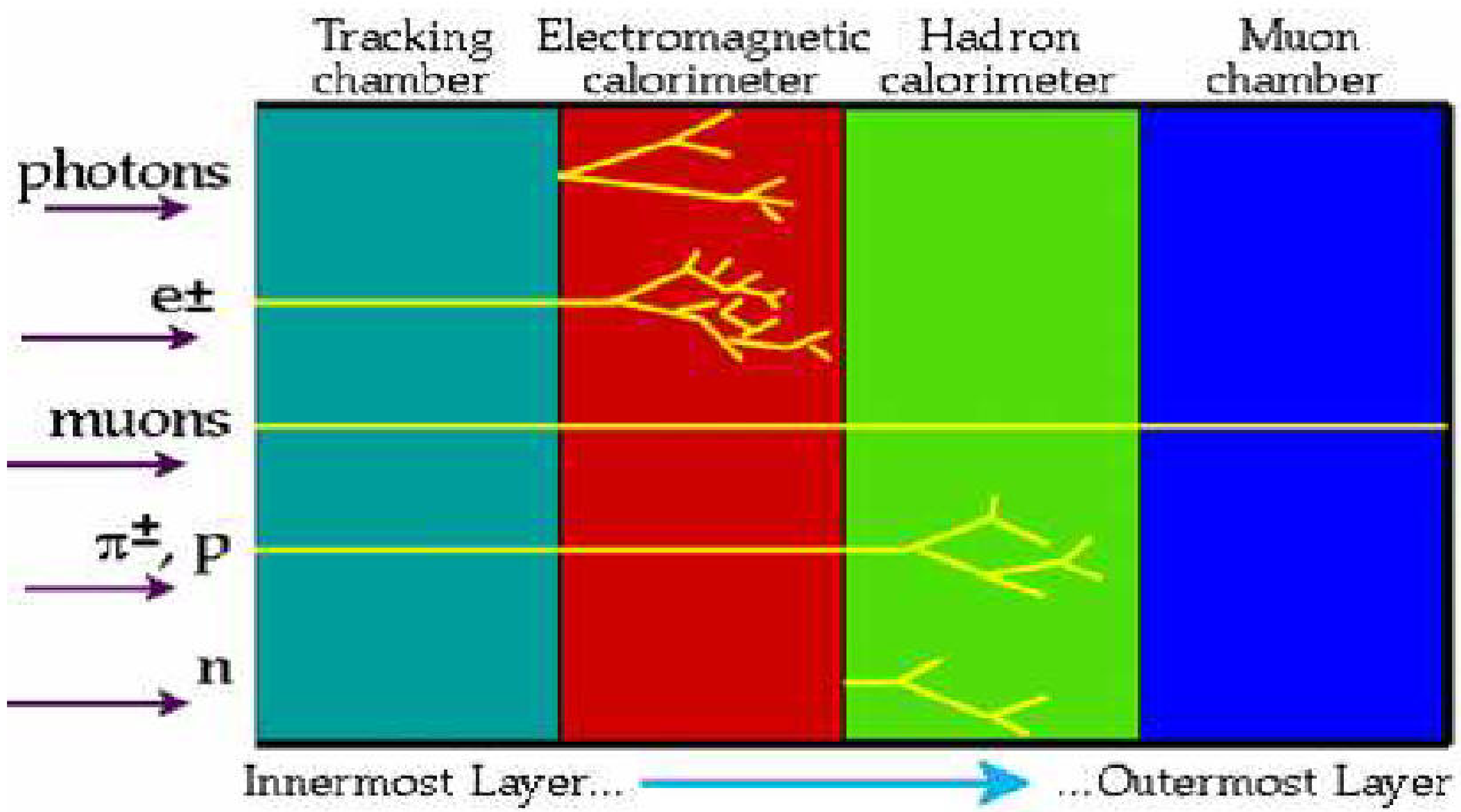
Models and Candidate Particles

- Benchmark Supersymmetry(SUSY) models
  - The Lightest SUSY Particle(LSP) is stable(R-parity) and neutral(Cosmology)
  - CMLLPs can be Next to Lightest SUSY Particles(NLSPs)
  - NLSPs can be long-lived

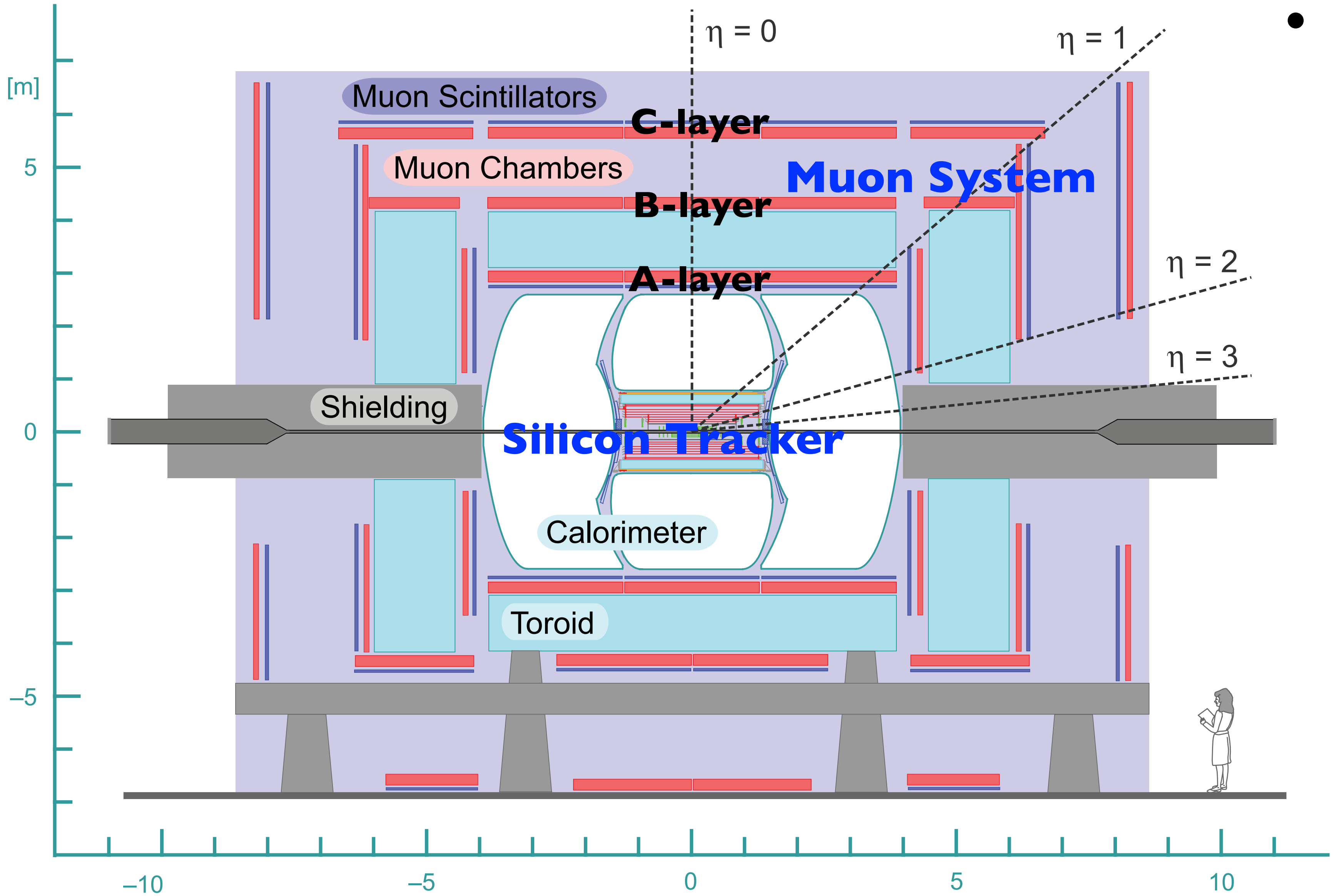
- CMLLP Candidates
  - Staus : Gauge Mediated SUSY Breaking(GMSB) with stau NLSP, if stau(NLSP) to gravitino(LSP) decays are suppressed
  - Charginos : if the mass difference between the lightest chargino and neutralino is smaller than 150 MeV, chargino can be long-lived, Anomaly Mediated SUSY Breaking(AMSB)
    - Chargino - mostly gaugino(gaugino-like chargino)
    - Chargino - mostly higgsino(higgsino-like chargino)
  - Stops : if Stop is the lightest colored particle, LSP(Hidden Valley)

CMLLPs in the D0 Detector

- **Charged : leaves tracks in the detector**
- **Massive : moves slowly(small β), and deposits more energy(large dE/dx)**
- **Long-Lived : has long life time, leaves the detector without decaying - detected by Muon system**
- **Looks like a slow moving muon, high P_T and large dE/dx**



The D0 Detector

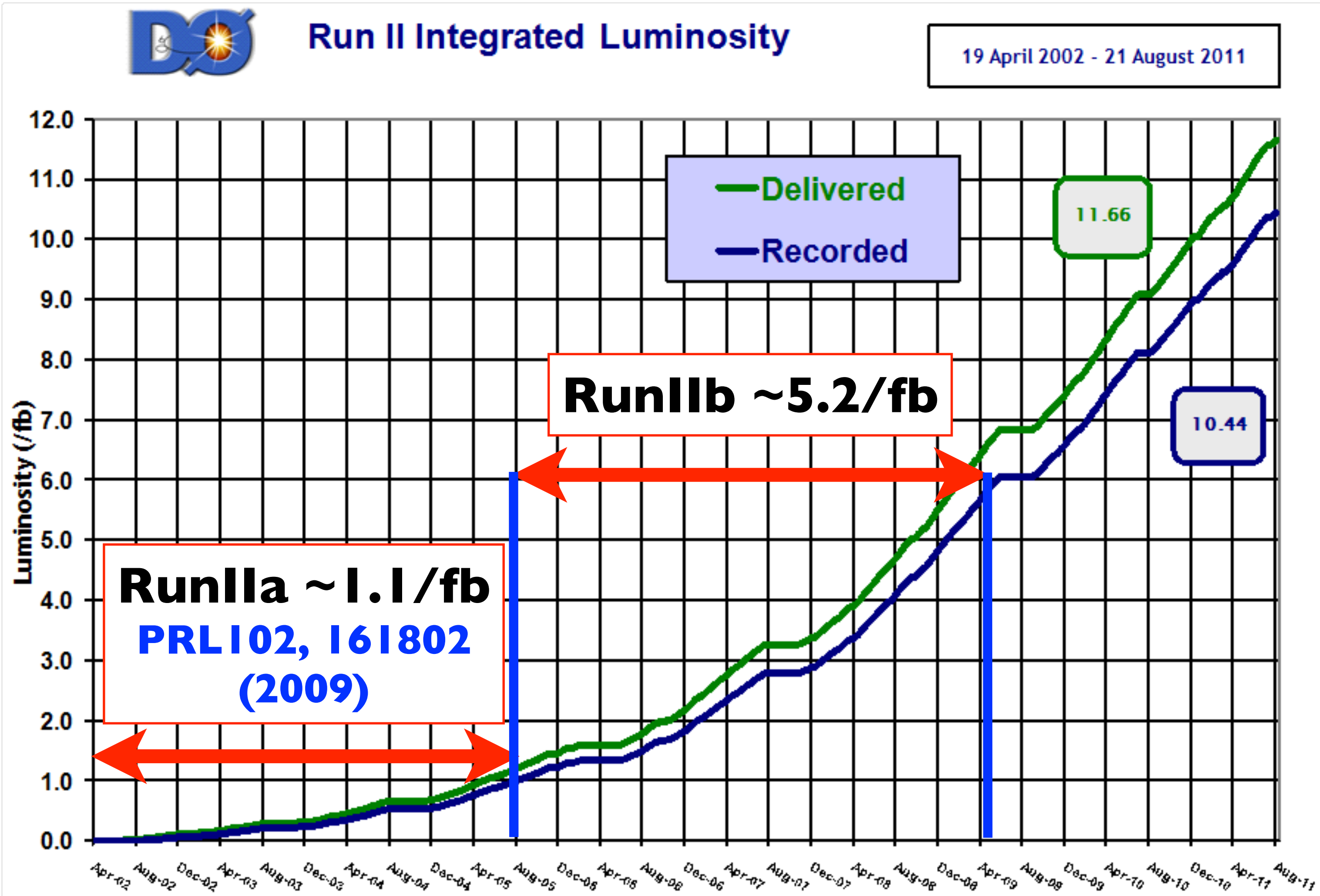


- **Muon System (for Speed) :**
  - **A, B,and C layer(1.8 T Toroid between A and BC Layer)**
  - **Wire chambers for muon tracking**
  - **Scintillators for muon triggering, time-of-flight information, timing gates for cosmic veto**
  - **Speed of light muons arrive in time, but CMLLPs are out-of -time**

- **Silicon Microstrip Tracker(for dE/dx) :**
  - **Tracking and vertexing**
  - **Muons are MIP(minimum ionizing particle)s, but CMLLPs are highly ionizing**

Signal, Background, and Data

- **Signals**
  - **Direct Pair Produced(little dependence on our benchmark SUSY models)** stau, gaugino-like, higgsino-like charginos, and stop by PYTHIA(100, 150, 200, 250, 300 GeV)
  - **D0 detector GEANT3 for detector response**
  - **External PYTHIA code for stop hadronization**
- **Background**
  - **Events with mis-measured(β and dE/dx) muons**
  - **from $W \rightarrow \mu\nu$ data**
- **Data**
  - **5.2/fb RunIIb Data**
  - **June/2006 ~ June/2009**
  - **Events Triggered by a high P_T(> 20 GeV) muon**

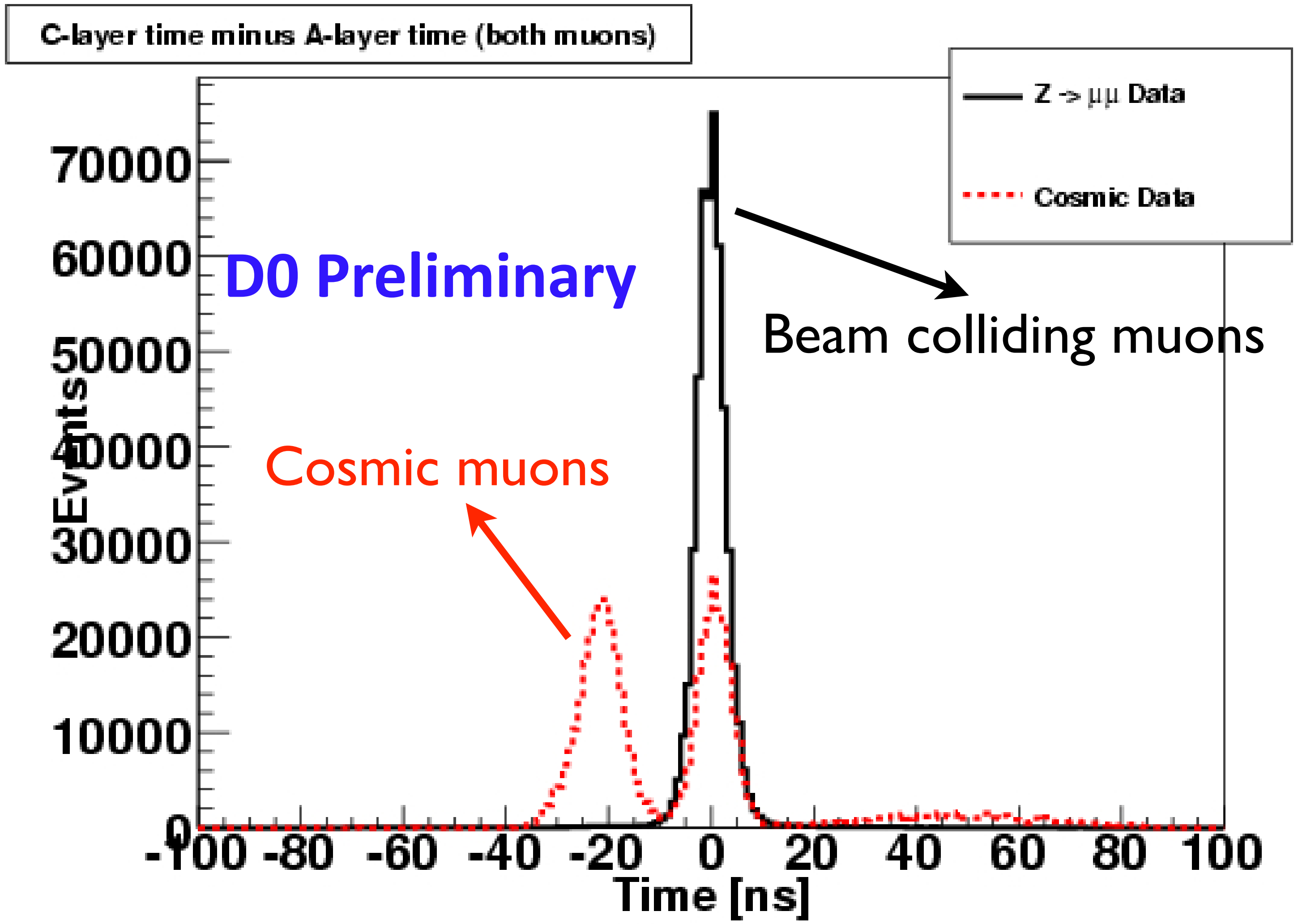


Event Selection

- Require **at least one muon** in an event
- If more than one muon, select the **highest P_T muon**
- **Single muon trigger** without scintillator timing cut
- Good muon qualities (**isolated**, matched to **good silicon tracks**)
- Cosmic muon rejected
  - DCA, Cosmic timing......
- High P_T(> 60 GeV)
- Speed(β) < 1
- Speed χ^2/d.o.f < 2

$$\beta = \sigma^2 \sum_i \frac{\beta_i}{\sigma_i^2}$$

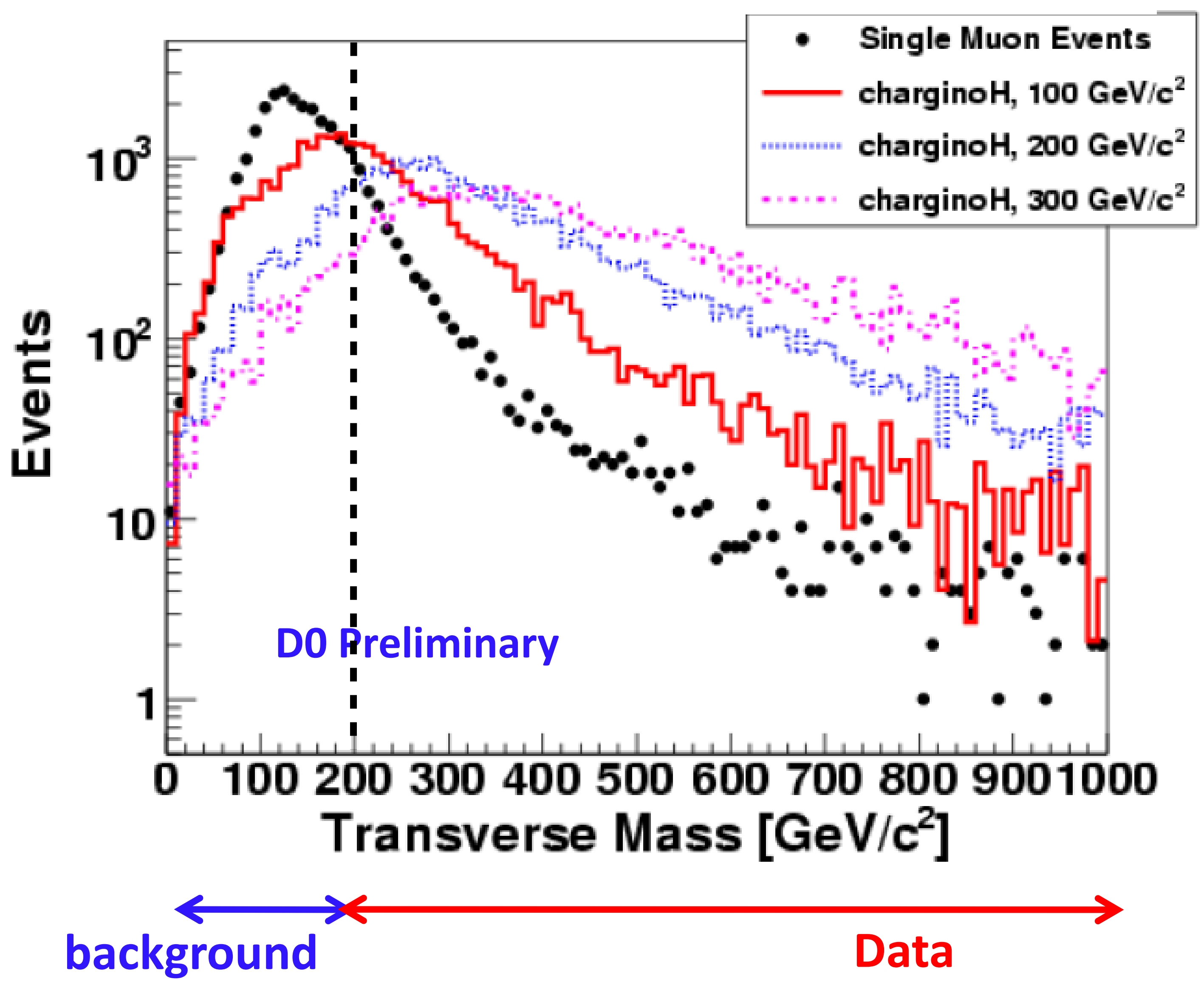
$$\chi^2 = \frac{1}{i-1} \sum_i \frac{(\beta - \beta_i)^2}{\sigma_i^2}$$



Background Sample

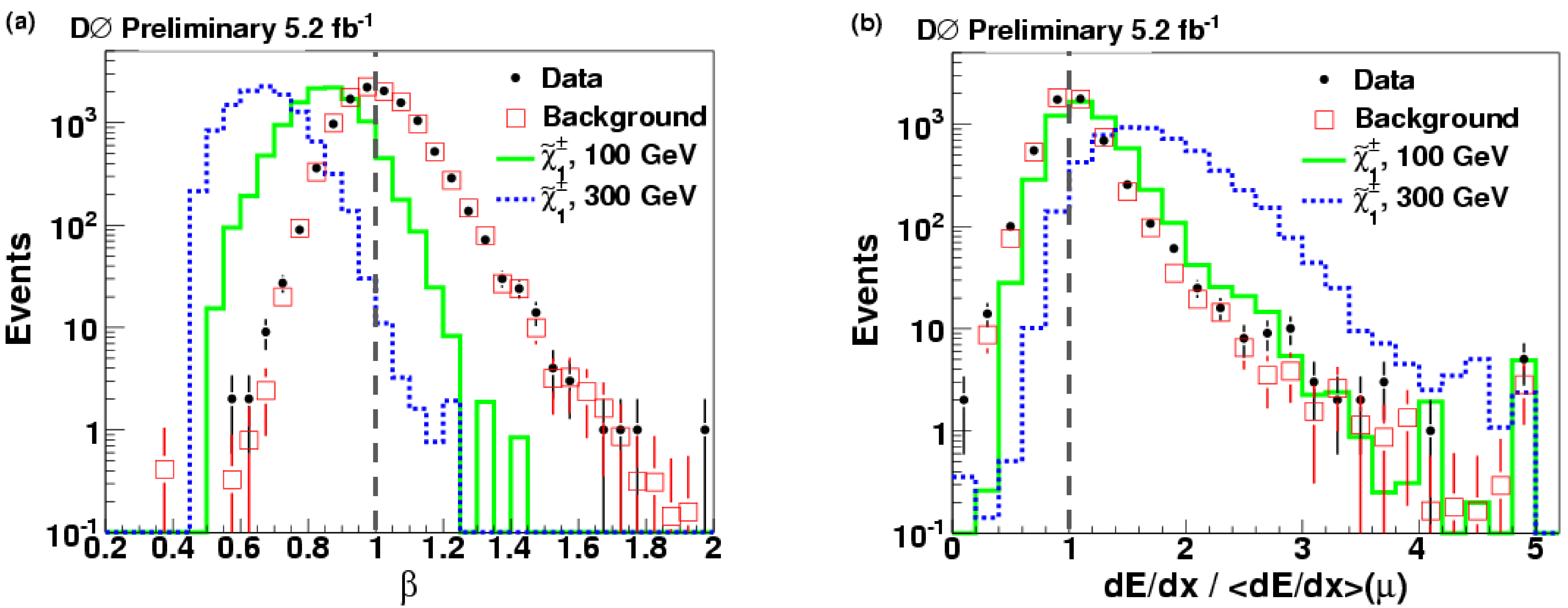
- **Background is mostly from W→μν channel**
- **M_T < 200 GeV for W dominated events from Data**
- **Background normalization is done using a signal free data sample β > 1**

$$M_T = \sqrt{(E_T + \not{E}_T)^2 - (p_x + \not{E}_x)^2 - (p_y + \not{E}_y)^2}$$



Speed and dE/dx

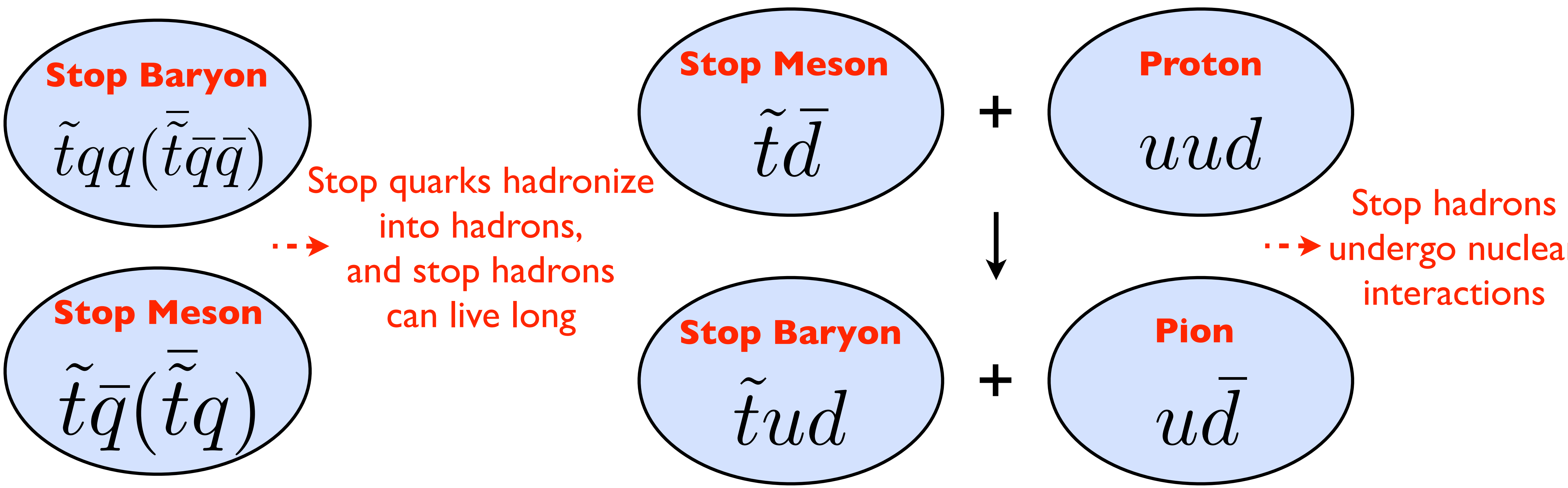
- **High P_T cut(> 60 GeV) reduces background**
- **Speed(β) and dE/dx are key variables to distinguish signal from background**



Timing and dE/dx calibrated so that muons are at β = dE/dx = 1

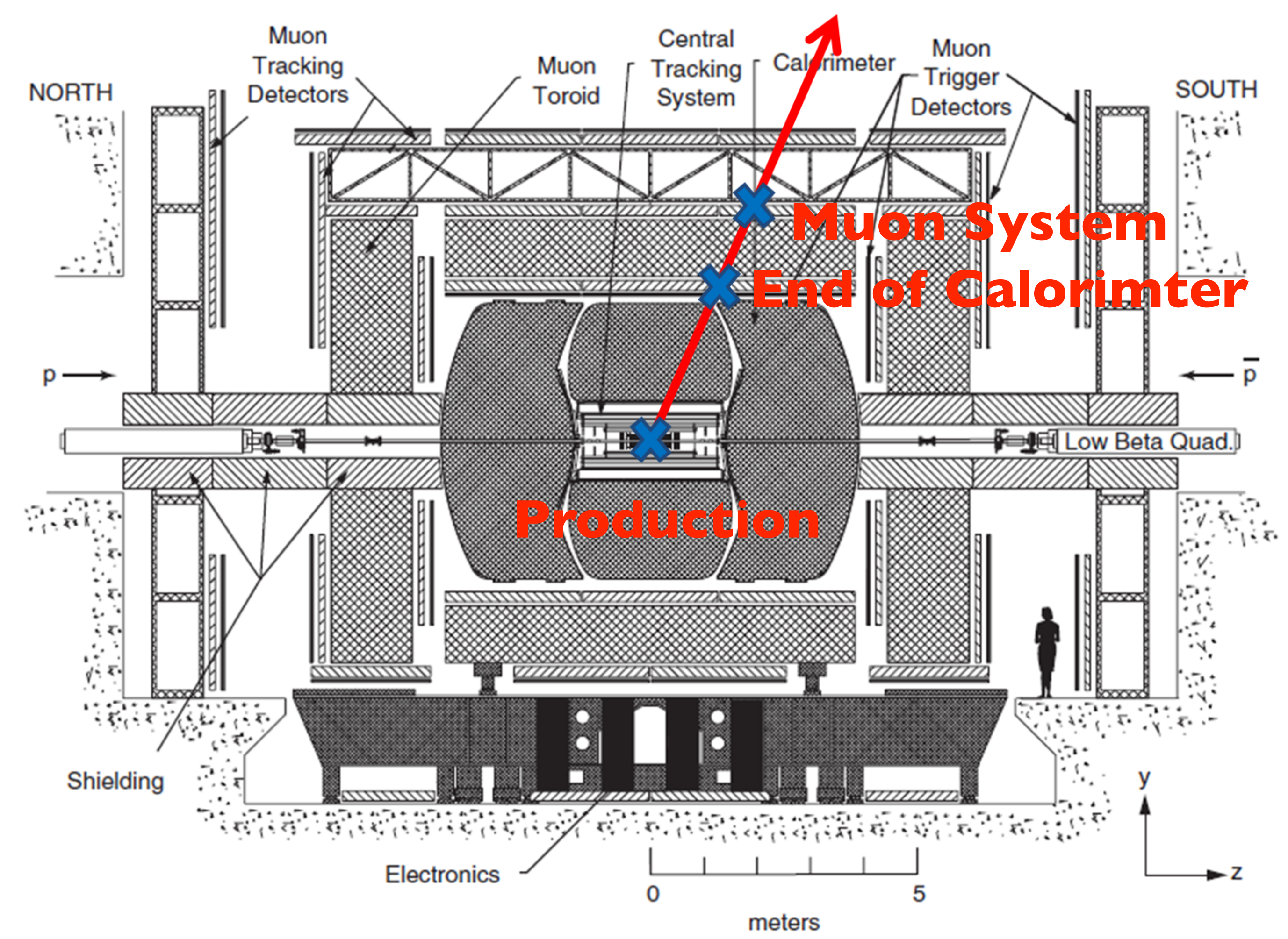
CMLLP Stop Search

- **Stop quarks hadronize into neutral/charged mesons or baryons**
- **Stop hadrons leave detectors without decay**
- **Stop hadrons undergo nuclear interactions with detector material**



Complications due to hadronization and charge exchange during nuclear interactions(charge flipping) for the stop CMLLP search - Stop Charge Survival Probability

Stop Charge Survival Probability



- **Based on the D0 detector material map, we can say that the stop hadron will undergo many nuclear interactions during its passage through the detector. Therefore, it will flip charge several times and will have no memory of initial charge**

- **Most stop hadrons will become baryons - 2/3 of them will be charged**

- **Most anti- stop hadrons will become mesons - 1/2 charged of them will be charged**

- **In order to detect stop hadron, it should be in the charged state, at the production, at the end of calorimeter, and after the muon toroid**

- **60% of stop(anti-stop) hadrons will be charged after hadronization**

- **27% of stop hadron will be charged at all 3 location**

- **15% of anti-stop hadron will be charged at all 3 location**

- **Probability that either(or both) stop hadron or anti-stop hadron can be charged is 38% - multiply to the stop signal acceptance**

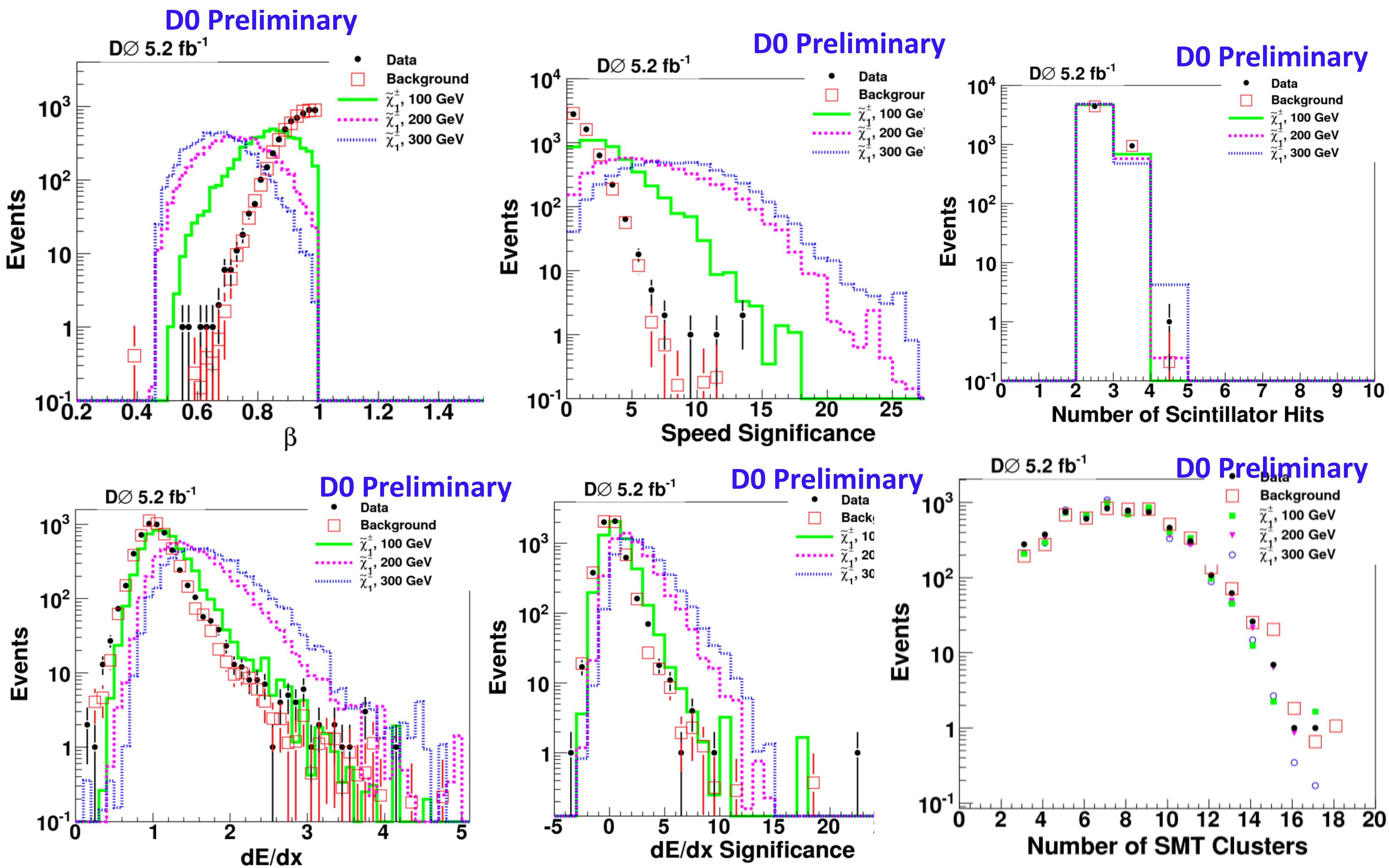
Multivariate Technique

- **To separate signal from background :**

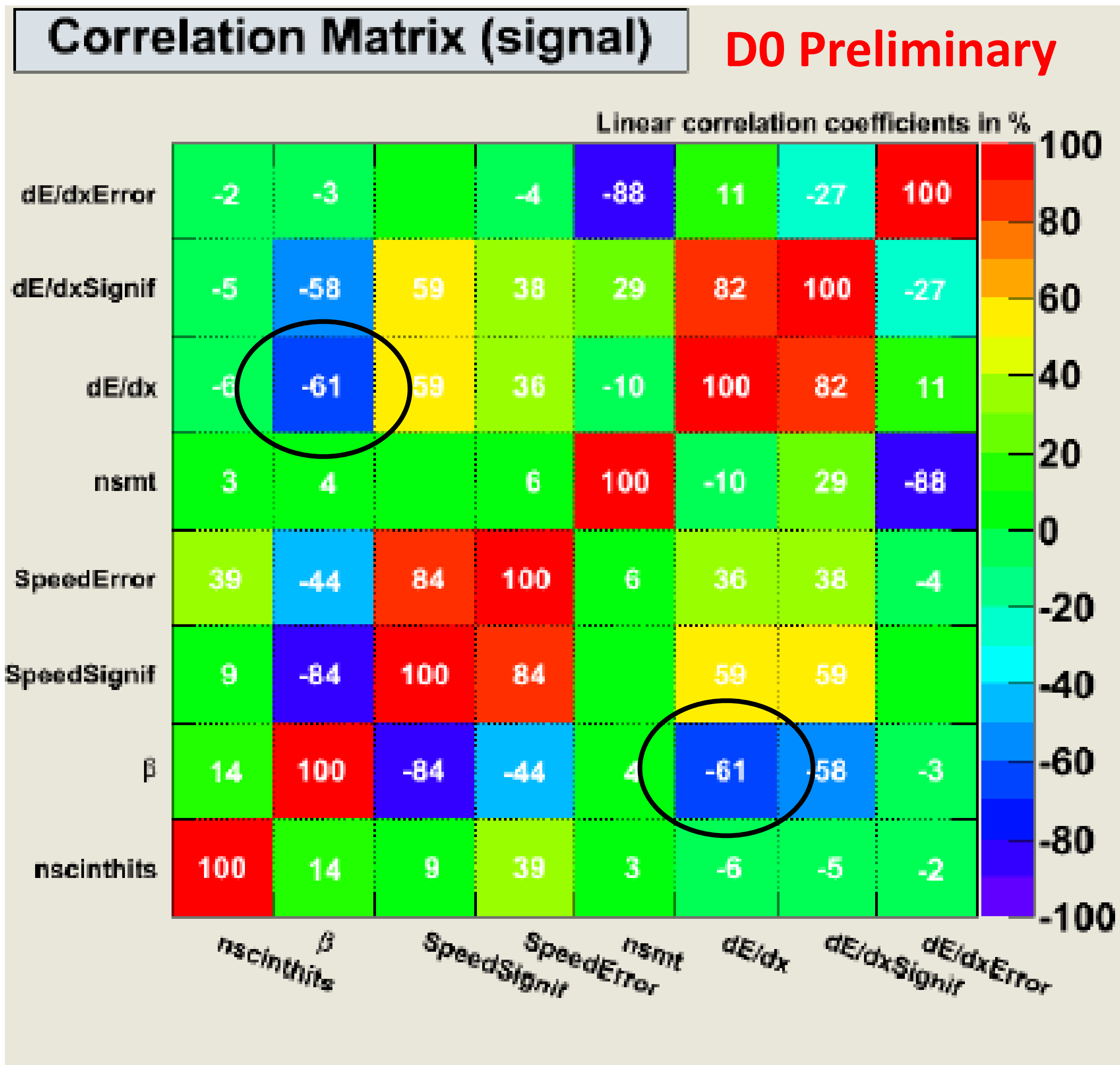
  - **Multivariate Techniques - Boosted Decision Tree(BDT)**
  - **Based on speed(β) and dE/dx related variables**
    - **Speed, Speed Significance, and the number of scintillator hits**
    - **dE/dx, dE/dx Significance, and the number of clusters in the Silicon tracker**
  - **Train BDT on signal, background, and data distribution to have our "final variable(BDT Output)" distributions**

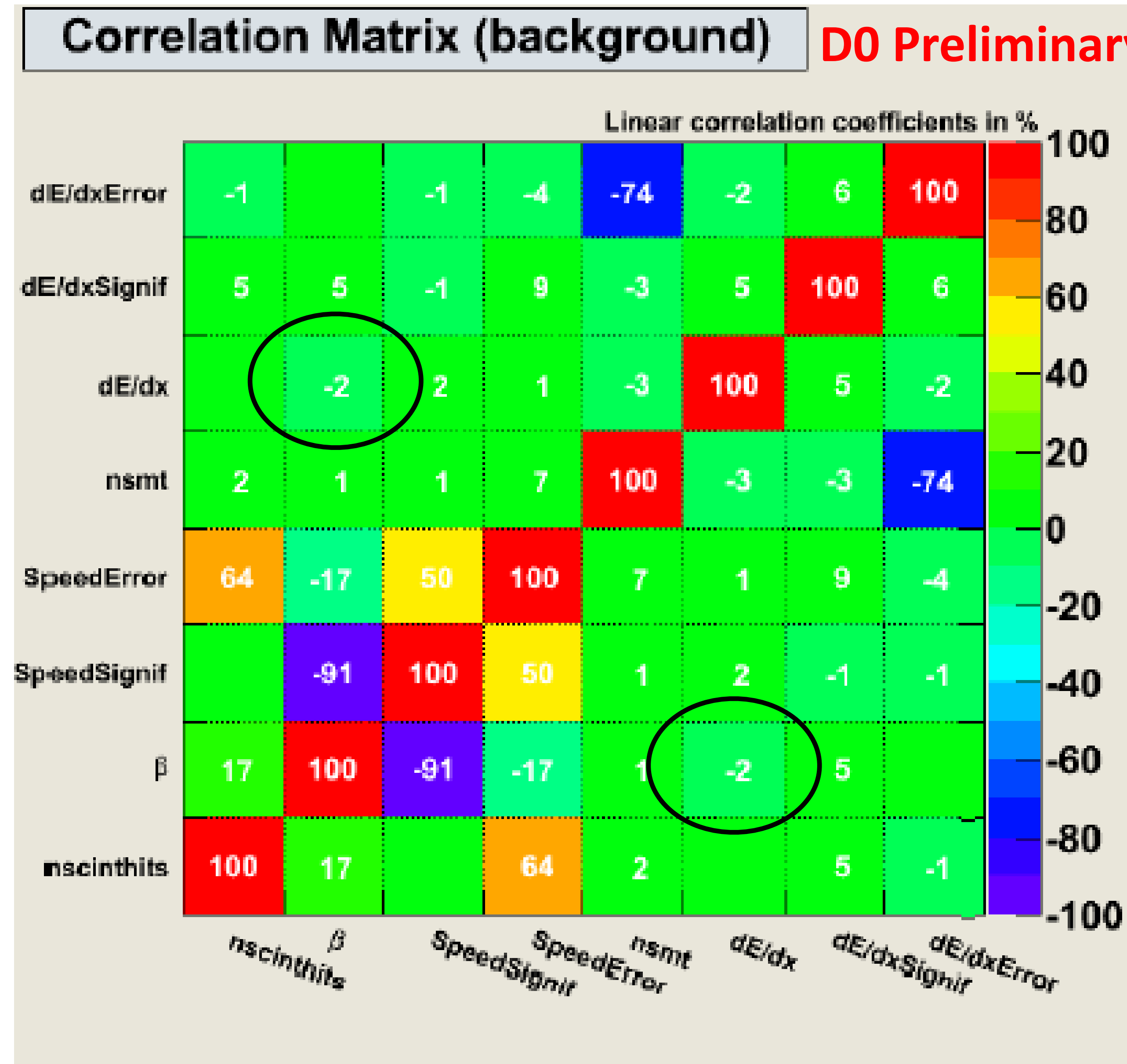
$$SpeedSig = \frac{1 - Speed}{\sigma_{Speed}} \qquad dE/dxSig = \frac{dE/dx - 1}{\sigma_{dE/dx}}$$

Input Variables to BDT



BDT Correlations

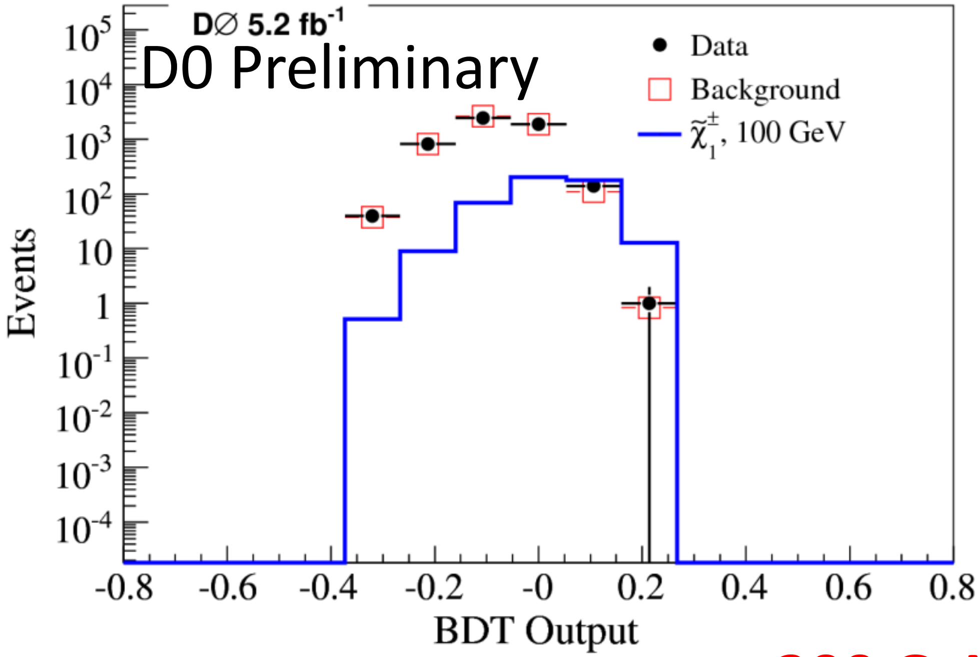




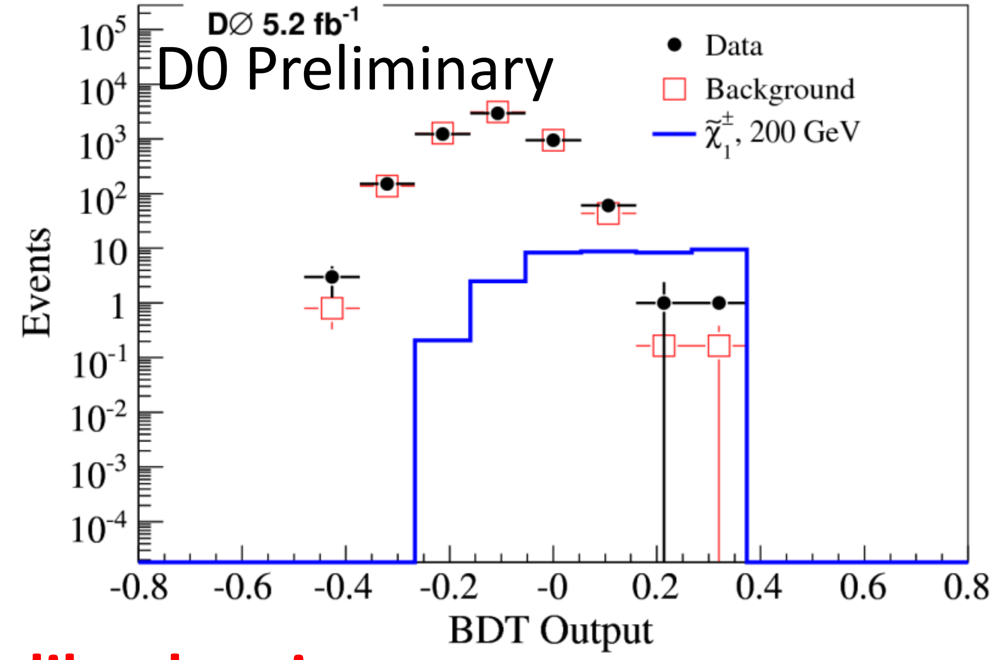
- **Speed and dE/dx are highly anti-correlated in signal but not in background**

BDT Distributions

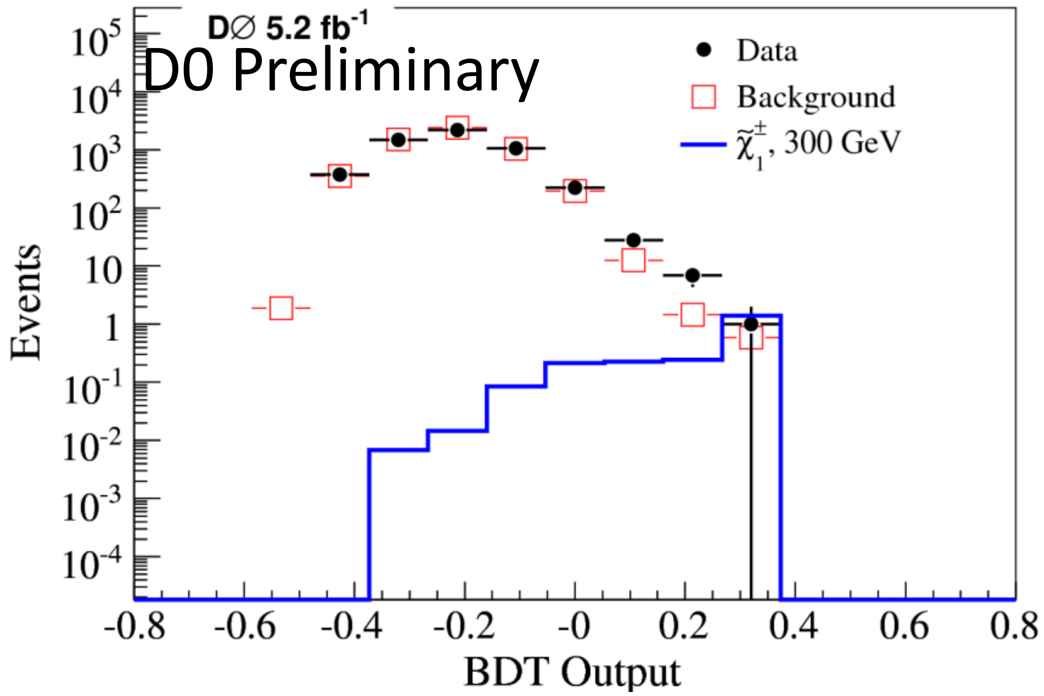
100 GeV gaugino-like chargino



200 GeV gaugino-like chargino



300 GeV gaugino-like chargino

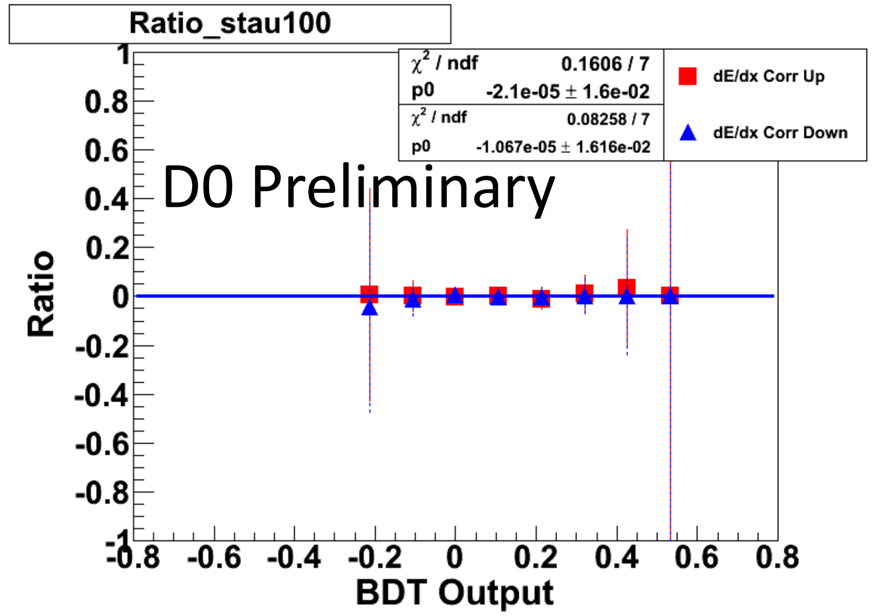


- **Data and background distributions are well matched - little possible signal**

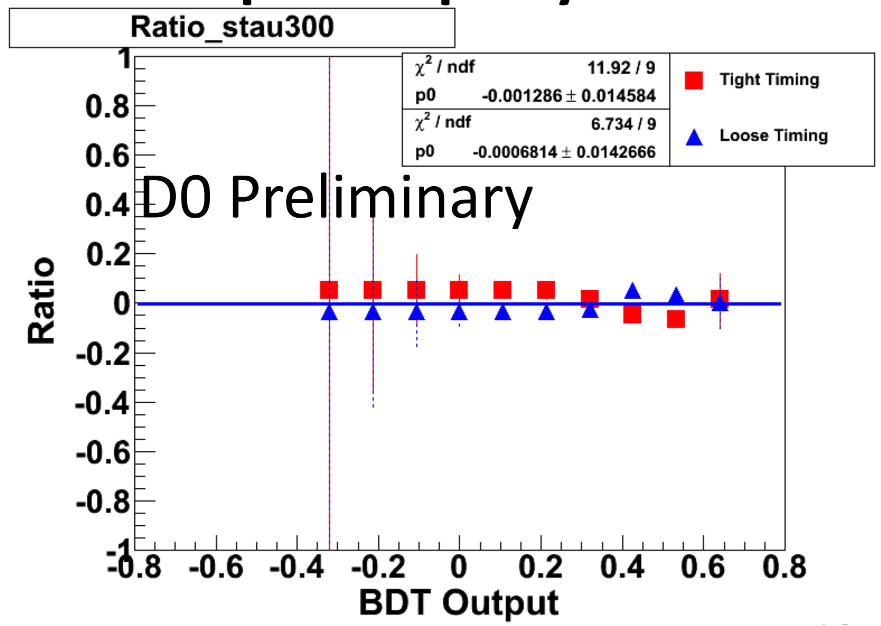
Systematic Uncertainties

- **Flat systematic Uncertainties :**
  - **Luminosity**
  - **MuonID**
  - **Background Normalization from the β cut**
  - **Background Normalization from the M_T cut**
  - **Muon P_T smearing**
  - **PDF**
  - **dE/dx Correction**
  - **dE/dx Simulation**
- **Shape systematic Uncertainties :**
  - **Trigger Timing Gate**
  - **Timing Simulation**

Example Flat Systematic



Example Shape Systematic



$$Ratio = \frac{BDT\_with\_systematic - BDT\_without\_systematic}{BDT\_without\_systematic}$$

Limit Setting

- CL(Confidence Level)$_s$ method to get 95% confidence level cross section limits
  - Semi-frequentist method
  - Log-Likelihood ratio(LLR) based on Poisson statistics
  - Integrate over LLR in pseudo-experiments to set confidence limits for background(CL_b) and signal+background(CL_{s+b})
  - 95% CL limit set where $CL_{s+b} / CL_b = 0.05$
- Put the final variable distributions(with systematic uncertainty) into the limit setting procedure

Cross Section Limits

D0 Preliminary

Staus

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	0.0121	0.0400	$0.0263^{+0.0109}_{-0.0075}$
150	0.00214	0.0418	$0.0164^{+0.0062}_{-0.0035}$
200	0.0004799	0.0113	$0.00671^{+0.00122}_{-0.00061}$
250	0.000122	0.0132	$0.00556^{+0.00114}_{-0.00077}$
300	0.0000314	0.00581	$0.00538^{+0.00104}_{-0.00076}$

Stops

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	15.6	0.562	$0.218^{+0.078}_{-0.062}$
150	1.58	0.133	$0.0490^{+0.0190}_{-0.0111}$
200	0.266	0.0529	$0.0234^{+0.0106}_{-0.0037}$
250	0.0560	0.0269	$0.0201^{+0.0090}_{-0.0050}$
300	0.0130	0.0794	$0.0529^{+0.0140}_{-0.0128}$

Gaugino-like Charginos

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	1.33	0.387	$0.153^{+0.068}_{-0.043}$
150	0.235	0.0435	$0.0167^{+0.0054}_{-0.0033}$
200	0.0566	0.0195	$0.00945^{+0.00368}_{-0.00057}$
250	0.0153	0.0136	$0.00988^{+0.00402}_{-0.00127}$
300	0.00417	0.0741	$0.0185^{+0.0046}_{-0.0027}$

Higgsino-like Charginos

Mass (GeV/c^2)	NLO Cross-Section [pb]	95% CL Limit [pb]	Expected Limit $\pm 1\sigma$ [pb]
100	0.381	0.106	$0.110^{+0.050}_{-0.032}$
150	0.0736	0.0417	$0.0165^{+0.0053}_{-0.0038}$
200	0.0186	0.0128	$0.00852^{+0.00169}_{-0.00112}$
250	0.00525	0.00897	$0.00716^{+0.00267}_{-0.00100}$
300	0.00154	0.0174	$0.0119^{+0.0033}_{-0.0005}$

Summary

- **Search for Charged Massive Long-Lived Particles in 5.2/fb of D0 Data**

  - **Multivariate Techniques(BDT) based on the speed and dE/dx related variables**
  - **Mass and Cross section Limits(95% CL)**
    - **265 GeV for stop (281 GeV without charge flipping)**
    - **251 GeV for gaugino-like chargino**
    - **230 GeV for higgsino-like chargino**

    Currently World Best!

    - **stau cross section limits between 0.04 and 0.006 pb, for masses between 100 and 300 GeV**

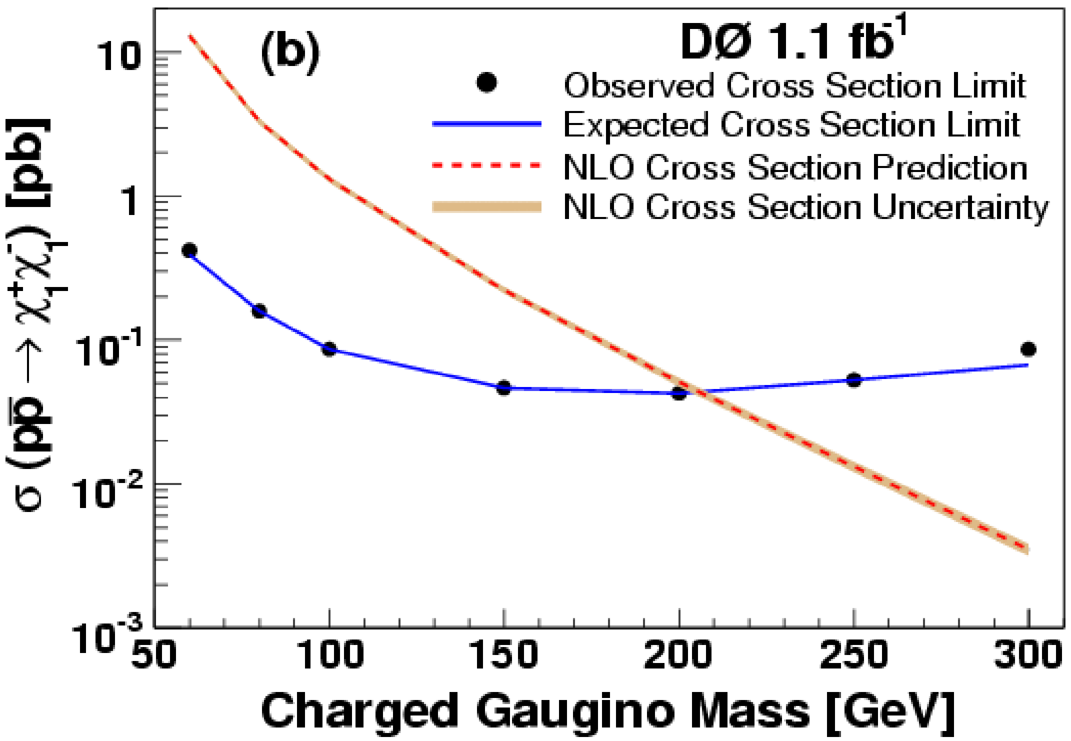
- **D0 public results : http://www-d0.fnal.gov/Run2Physics/WWW/results.htm**

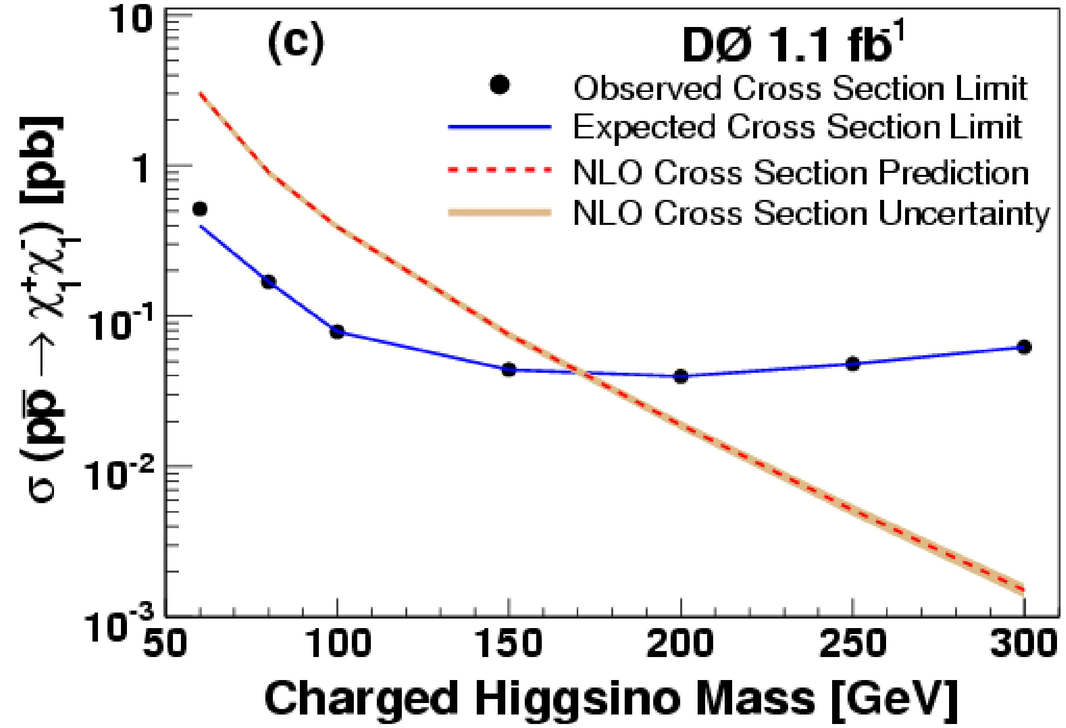
Thank you!

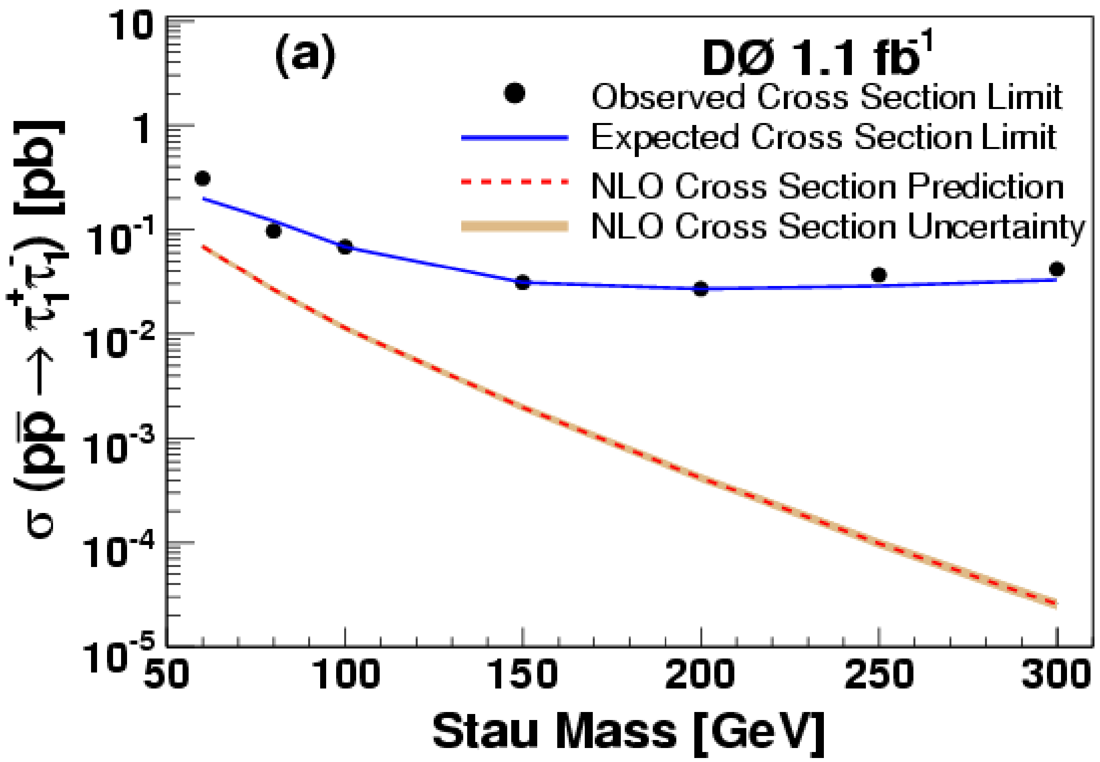
Backup Slides

RunIIa Results

D0 Published Results







Data set – 1.1 fb-1

Cross section limit for

Stable staus – 0.31 pb to 0.04 pb in the mass range 60 to 300 GeV

Mass limit for

Chargino (gaugino type) – 206 GeV

Charginoh (Higgsino type) – 171 GeV

Published - PRL 102 , 161802 (2009)

Events Table

Expected No. of Events

With BDT>0.27 cut

D0 Preliminary

Stau

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.74 \pm 0.001(\text{stat.}) \pm 0.08(\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$3.49 \pm 0.001 \pm 0.08$	$2.43 \pm 0.001 \pm 0.18$	4
200	$5.48 \pm 0.001 \pm 0.35$	$1.11 \pm 0.001 \pm 0.08$	2
250	$7.14 \pm 0.001 \pm 0.43$	$1.24 \pm 0.001 \pm 0.09$	7
300	$7.74 \pm 0.01 \pm 0.33$	$2.63 \pm 0.001 \pm 0.20$	3

Stop

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.01 \pm 0.001(\text{stat.}) \pm 0.001(\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$0.72 \pm 0.001 \pm 0.08$	$0.25 \pm 0.001 \pm 0.02$	2
200	$2.09 \pm 0.001 \pm 0.16$	$0.59 \pm 0.001 \pm 0.04$	3
250	$2.63 \pm 0.001 \pm 0.17$	$1.70 \pm 0.001 \pm 0.13$	1
300	$2.75 \pm 0.001 \pm 0.17$	$3.01 \pm 0.001 \pm 0.23$	2
350	$2.57 \pm 0.001 \pm 0.21$	$1.05 \pm 0.001 \pm 0.08$	4
400	$2.47 \pm 0.001 \pm 0.16$	$0.53 \pm 0.001 \pm 0.04$	1

Gaugino-like chargino

Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$2.54 \pm 0.001 \pm 0.16$	$0.25 \pm 0.001 \pm 0.02$	2
200	$2.04 \pm 0.001 \pm 0.79$	$0.17 \pm 0.001 \pm 0.01$	0
250	$4.63 \pm 0.001 \pm 0.36$	$0.51 \pm 0.001 \pm 0.04$	1
300	$4.58 \pm 0.001 \pm 0.47$	$0.59 \pm 0.001 \pm 0.04$	1

Higgsino-like chargino

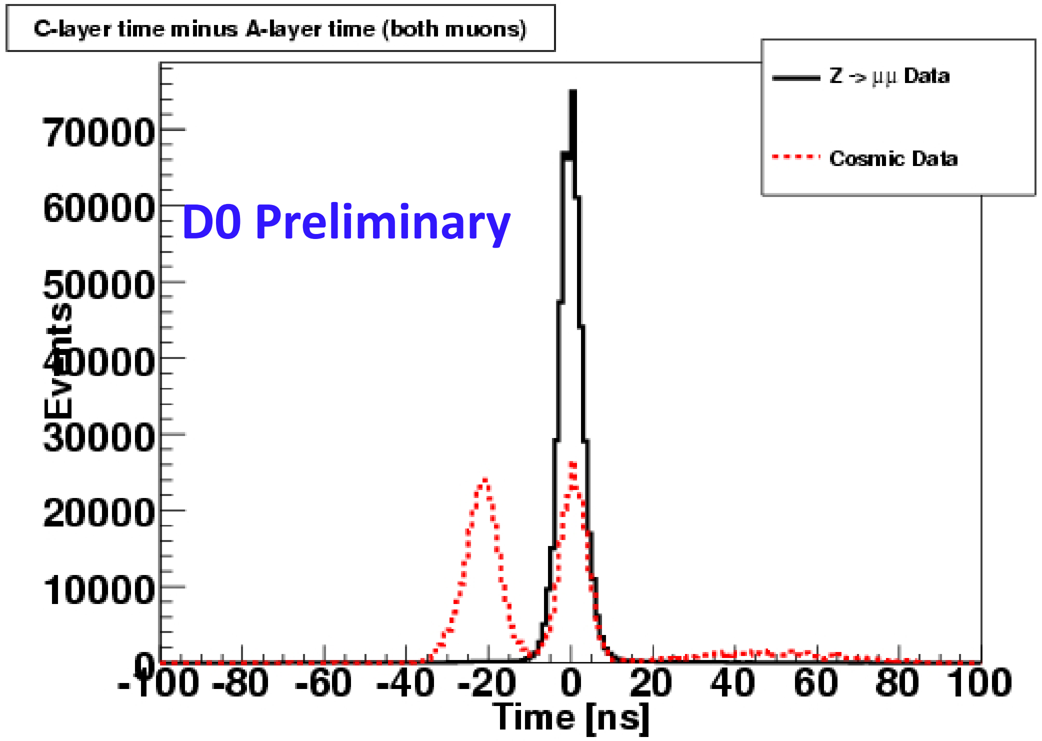
Mass (GeV)	Signal Acceptance (%)	Predicted Background	Observed Data
100	$0.29 \pm 0.001(\text{stat.}) \pm 0.11\ (\text{sys.})$	$0 \pm 0(\text{stat.}) \pm 0(\text{sys.})$	0
150	$3.57 \pm 0.001 \pm 0.26$	$0.87 \pm 0.001 \pm 0.07$	3
200	$5.68 \pm 0.001 \pm 0.34$	$1.75 \pm 0.001 \pm 0.13$	5
250	$5.21 \pm 0.001 \pm 0.62$	$0.79 \pm 0.001 \pm 0.06$	2
300	$4.60 \pm 0.001 \pm 0.36$	$0.36 \pm 0.001 \pm 0.03$	0

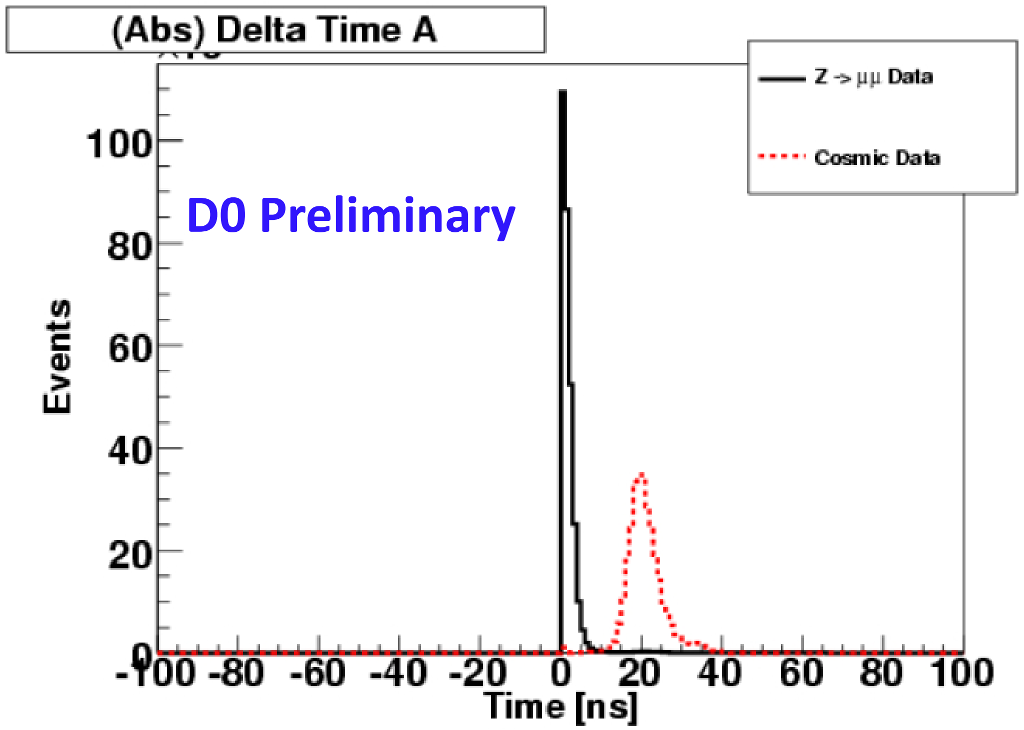
Cosmic Rejection

Cosmic Ray Muon rejection

Proton-Antiproton Collision

- The highest p_T muon must have:
  - dca< 0.2 cm
  - (C-layer time) - (A-layer time) > -10 ns
- If there are exactly 2 muons in event, event is rejected if
  - dca of either muon > 0.2 cm
  - | A layer time for Muon 1 – A layer time for Muon 2| > 10 ns
  - The C-layer time minus the A-layer time for either muon < -10 ns.
  - pseudo-acolinearity: $\Delta\alpha = |\Delta\phi + \Delta\theta - 2\pi| < 0.05$





Background Normalization

normalization region

B>1	**Normalization background**	**Normalization data**
β<1	**Event background**	**Event data**
	mT<200 GeV	mT>200 GeV

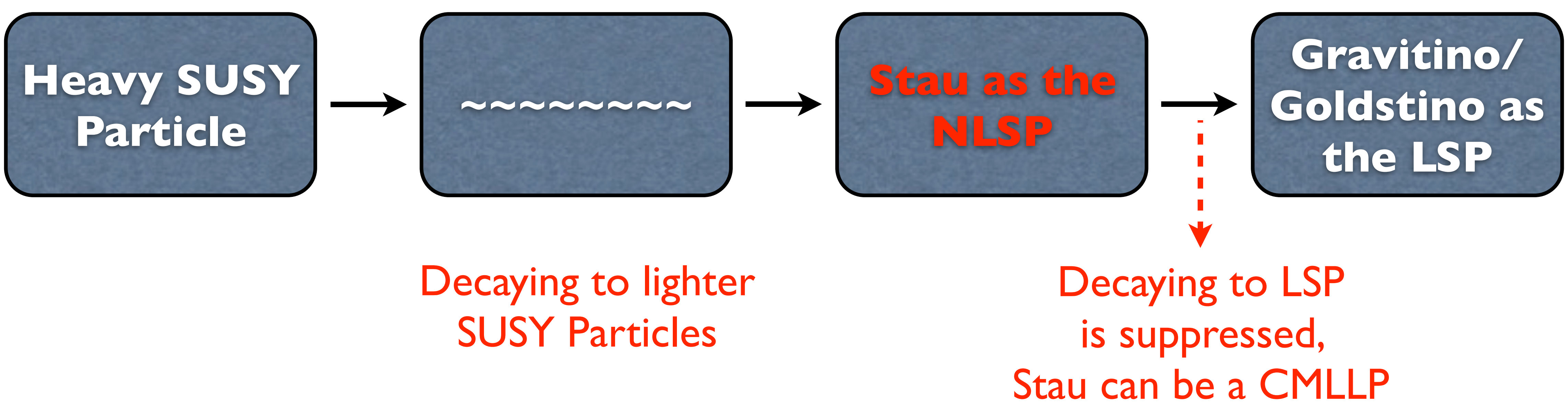
Normalized background = **Backgroundevents*Normalization data events/ Normalization background events**

Staus as CMLLPs

Gauge Mediated Supersymmetry Breaking :

- **Sub case of the Flavor-respecting Minimal Supersymmetric Standard Model**
- **New chiral-supermultiplet and messengers - couple to the SUSY breaking source**
- **Gravitino/Goldstino is the LSP, stau can be the NLSP by the choice of parameter - model lineD**

Parameter	Description	Value
Λ_m	Scale of SUSY breaking	19 to 100 TeV
M_m	Messenger mass scale	$2\Lambda_m$
N_5	Number of messenger fields	3
$tan\beta$	Ratio of Higgs VEVs	15
$sgn\mu$	Sign of Higgsino mass term	$+1$
C_{grav}	Factor multiplying effective mass of gravitino	1



Charginos as CMLLPs

Anomaly-Mediated Supersymmetry Breaking or models that do not have gaugino mass unification :

- **The average traveling distance of a chargino with energy E :**

$$L = \left(\frac{GeV}{m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}}\right)^5 \sqrt{\frac{E^2}{m^2_{\tilde{\chi}_1^\pm}} - 1} \times 10^{-2}\ cm$$

If the mass difference between the lightest neutralino and chargino is less than 150 MeV, chargino can be a CMLLP

- **2 general cases are possible :**

Model	gaugino-like chargino	higgsino-like chargino
μ(GeV)	$10,000$	varies from 60 to 300
M_1(GeV)	$3M_2$	$100,000$
M_2(GeV)	varies from 60 to 300	$100,000$
M_3(GeV)	500	500
$\tan\beta$	15	15
Squark Mass (GeV)	800	800

$\tilde{\chi}_1^\pm \rightarrow$

mostly gaugino : Gaugino-like Chargino
mostly higgsino : Higgsino-like Chargino

Stops as CMLLPs

Various SUSY and the beyond SM models predict top scalar quarks are the lightest colored or long-lived particles

- **Stops hadronize into charged or neutral hadrons(mesons and baryons)**
- **Stop hadrons do not decay and live long enough to be CMLLP candidates**
- **Stop hadrons do nuclear interaction in the material**

Complications of hadronization and charge exchanging during nuclear interaction

Stop Baryon
$\tilde{t}qq(\bar{\tilde{t}}\bar{q}\bar{q})$

Stop Meson
$\tilde{t}\bar{q}(\bar{\tilde{t}}q)$

Stop hadronize into hadrons, and stop hadrons can live long

Stop Meson $\tilde{t}\bar{d}$ + **Proton** uud

$\downarrow$

Stop Baryon $\tilde{t}ud$ + **Pion** $u\bar{d}$

Stop hadrons do nuclear interaction

The D0 Detector - 5

- **Muon Wire Chambers**
  - **Forward region - A (4 decks), B and C (3 decks) layer Mini-Drift-Tube(MDT)**
  - **Central region - A(4 decks), B and C(3 decks) layer Proportional-Drift-Tube(PDT)**
  - **Muon Tracking - Drift time**
- **Muon Scintillator Counters**
  - **Forward region - A, B and C layer Pixels**
  - **Central region -**
    - **A layer : A-phi counter**
    - **B layer : Side, Bottom**
    - **C layer : Cosmic cap(top-side), Cosmic Bottom (bottom)**
  - **All scintillator counters(including electronics) are adjusted so that the speed of light particles arrive at the center of scintillator counters from the colliding points at the time of zero - T0**

Scintillator	Read-out Gate [ns]	L1 Trigger Gate [ns]
All Forward layers	[-15, 85]	[-15, 15]
Central A-layer	[-12, 88]	[-12, 12]
Central B-layer Sides	[-42, 58]	[-42, 42]
Central B-layer Bottom	[-25, 75]	[-25, 25]
Central C-layer Top and Sides	[-23, 77]	[-23, 23]
Central C-layer Bottom	[-30, 70]	[-30, 30]

The Tevatron Complex - 5

The Tevatron

- **36 proton and antiproton bunches(396 nsec) are accelerated 0.98 TeV**
- **Superconducting magnet(4.2 T)**
- **Proton - antiproton collider with the center of mass energy 1.96 TeV**
- **Instantaneous luminosity ~4e32 /cm^2 sec**